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Blunted Endogenous Opioid Release Following an Oral Dexamphetamine Challenge in Abstinent Alcohol Dependent Individuals

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ABSTRACT

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Addiction has been proposed as a 'reward deficient' state which is compensated for with substance use. There is growing evidence of dysregulation in the opioid system, which plays a key role in reward, underpinning addiction. Low levels of endogenous opioids are implicated in vulnerability for developing alcohol dependence (AD) and high mu-opioid receptor (MOR) availability in early abstinence is associated with greater craving. This high MOR availability is proposed to be the target of opioid antagonist medication to prevent relapse. However, changes in endogenous opioid tone in AD are poorly characterised and are important to understand as opioid antagonists do not help everyone with AD. We used [^{11}C]carfentanil, a selective mu-opioid receptor (MOR) agonist PET radioligand, to investigate endogenous opioid tone in AD for the first time. We recruited 13 abstinent male AD and 15 control participants who underwent two [^{11}C]carfentanil PET scans, one before and one 3 hours following a 0.5 mg/kg oral dose of dexamphetamine to measure baseline MOR availability and endogenous opioid release. We found significantly blunted dexamphetamine-induced opioid release in 5 out of 10 regions-of-interest including insula, frontal lobe and putamen in AD compared with controls, but no significantly higher MOR availability AD participants compared with HC in any region. This study is comparable to our previous results of blunted dexamphetamine-induced opioid release in gambling disorder, suggesting that this dysregulation in opioid tone is common to both behavioural and substance addictions.

1 MAIN ARTICLE

3 Word count = 3903

6 INTRODUCTION

8 Alcohol dependence affects 4% of adults in Europe and 4.7% in the US, and globally 3.3
9 million deaths per year (5.9% of deaths worldwide) are attributed to harmful alcohol use ¹.
10 Treatment for alcohol abuse and dependence costs an estimated \$12 billion in the US and
11 €5 billion in the EU ^{2,3}, however three quarters of individuals with alcohol dependence will
12 not remain abstinent from alcohol in the first year following treatment ⁴. Thus, there is a
13 substantial unmet need in reducing this harm.

15 Psychosocial approaches are the mainstay treatment of alcohol dependence but effective
16 relapse prevention medications, including the opioid antagonists naltrexone and nalmefene,
17 are available ⁵⁻⁷. Opioid antagonists modulate the mesolimbic ‘reward’ pathway, which is
18 proposed to underpin their effectiveness in reducing the risk of relapse to heavy drinking <sup>5,7-
19 9</sup>. Using functional magnetic resonance imaging (fMRI), naltrexone and nalmefene have
20 been shown to reduce brain responses in the mesolimbic pathway to salient alcohol cues or
21 exposure ^{10,11}. These medications do not help everyone and so a better understanding of
22 opioid system function in alcoholism is required to develop improved therapies and better
23 target individuals with current medication.

The mu opioid receptor (MOR) subtype is expressed in brain regions associated with addiction including the ventral tegmental area, nucleus accumbens and amygdala. The MOR and its endogenous ligands, including β -endorphin, play an important role in reward^{12–14}. Some substances of abuse, including alcohol and amphetamines, increase the levels of endogenous opioids binding to MORs and this is associated with positive subjective effects, including ‘best ever’ feelings and euphoria^{15,16}. Naltrexone has been shown to attenuate these positive subjective effects^{17–19}. Endogenous opioid dysregulation may also play an important role in the vulnerability to developing addiction where a ‘reward deficient’ state leads to substance abuse to compensate for opioidergic hypofunction^{20,21}.

Lower basal endogenous opioid levels in the brain may result in higher opioid receptor availability and this has been demonstrated in alcohol dependence during early abstinence using the non-selective radioligand [¹¹C]diprenorphine²² and the MOR selective radioligand [¹¹C]carfentanil^{23,24}. Higher opioid receptor availability is associated with alcohol craving^{22,23,25} and alcohol dependent individuals with higher [¹¹C]carfentanil binding may benefit more from naltrexone treatment²⁵. This suggests that the effectiveness of opioid antagonists is linked to opioid receptor availability in humans. However, no studies have assessed *in vivo* endogenous opioid tone in alcohol dependence which is also key to understanding the predictors of response to opioid antagonists.

We have developed and validated a [¹¹C]carfentanil positron emission tomography (PET) protocol to assess endogenous opioid release following an oral dexamphetamine challenge^{15,26}. With this protocol, we demonstrated no difference in baseline MOR availability but a blunted dexamphetamine-induced opioid release, with blunted associated subjective

1 effects, in gambling disorder ²⁷. In this study, we applied the same protocol to test the
2 hypotheses that in alcohol dependence there is blunted dexamphetamine induced
3 endogenous opioid release, as shown in gambling disorder, and a higher baseline MOR
4 availability.

5

PATIENTS AND METHODS

This study was approved by the West London Research Ethics Committee and the Administration of Radioactive Substances Advisory Committee, UK (14/LO/1552). Written informed consent was obtained from all the participants.

Alcohol dependent (AD) men (n=13, >4 weeks abstinent, DSM-5 criteria for 'severe' alcohol use disorder) were recruited from Central North West London NHS Foundation Trust, UK and associated services. Severity of alcohol dependence, relapse risk and alcohol craving were assessed using the Severity of Alcohol Dependence Questionnaire (SADQ)²⁸, Time to Relapse Questionnaire (TRQ)²⁹ and Alcohol Urge Questionnaire (AUQ)³⁰. 'High risk' alcohol exposure was calculated as lifetime cumulative weeks with >60g average daily alcohol consumption³¹. Male healthy controls (HC) (n=15) included ten from previous studies^{15,26} and five recruited for the current study to achieve age-matching between groups.

All participants' physical and mental health history, including history of alcohol, tobacco and substance use, was assessed by psychiatrists using the Mini International Neuropsychiatric Interview (MINI-5)³². Current or past history of gambling disorder or substance dependence (excluding nicotine) was an exclusion criterion; previous recreational drug use was allowed (>10 times in lifetime: cannabis: 3 HC, 9 AD, cocaine: 6 AD, stimulants: 5 AD, inhalants: 1 HC, 3 AD, hallucinogens: 1 AD, sedatives: 1 AD, 2 HC, opioids: 1 AD). HC were excluded if they drank >21 UK units of alcohol (166g) per week or had a previous history of alcohol dependence. Drug use (except nicotine) was not permitted 2 weeks prior to the study visits and confirmed by negative urine drug screen (cocaine, amphetamine, THC, methadone,

opioids, benzodiazepines). Participants were breathalysed for alcohol. Smoking tobacco was not allowed 1 hour before each scan. All participants had laboratory and ECG results within normal range, and were not prescribed any regular psychotropic medications.

Participants with current or previous psychiatric disorders were excluded. However, in AD participants a past history of depression (non-psychotic) and/or anxiety disorders was permitted due to the high prevalence in this population. Depression was assessed with the Beck Depression Inventory (BDI) ³³ and anxiety with Spielberger State/Trait Inventory (SSAI and STAI) ³⁴. Impulsivity was assessed with the UPPS-P Impulsive Behaviour Scale ³⁵.

Genotyping

Blood samples for genotyping of OPRM1 A118G polymorphism were available from all participants (AD: n=13; HC: n=11) except for 4 HC from our first study ¹⁵ and were analysed by LGC Limited (Middlesex, UK). DNA was extracted and normalised and underwent SNP-specific KASPTM Assay mix. Loci with a call rate less than 90% were not included. Participants were categorised as a G-allele carrier (G:A or G:G) or not (A:A).

PET and MR Imaging protocol

We followed our protocol as previously described ^{15,26,27}. [¹¹C]carfentanil PET scans were acquired on a HiRez Biograph 6 PET/CT scanner (Siemens Healthcare, Erlangen, Germany). Dynamic emission data were collected continuously for 90 min (26 frames, 8 × 15 s, 3 × 60 s, 5 × 120 s, 5 × 300 s, 5 × 600 s) following an intravenous bolus infusion of maximum 350MBq [¹¹C]carfentanil infused over 20 seconds. Participants underwent two [¹¹C]carfentanil PET scans, one before and one 3 hours following the oral administration of 0.5mg/kg

dexamphetamine. 7 participants (n=1 AD, n=7 HV) underwent scans on separate days.

However, there were no significant effects of this on [¹¹C]carfentanil binding potential (BP_{ND}).

Subjective responses to dexamphetamine challenge were measured with the Simplified Amphetamine Interview Rating Scale (SAIRS) (15 mins pre-dose (baseline), 1, 2, 3, 4.5h post-dose)³⁶, and Spielberger State Anxiety Inventory (SSAI) (before and after each PET scan).

Blood samples to measure plasma dexamphetamine levels were obtained pre-dose (baseline), 1, 2, 3, and 4.5 hours post-dosing. Dexamphetamine samples were analysed at the Drug Control Centre, Analytical and Environmental Sciences, King's College London, UK. Serum cortisol samples were collected immediately pre-dexamphetamine dose (baseline), 30, 60, 90, 120, 150 and 180 minutes post-dose. Cortisol samples were analysed using the ARCHITECT cortisol assay at the Pathology Department, Hammersmith Hospital, Imperial College Healthcare NHS Trust, London, UK. See Supplementary data for further details of cortisol and amphetamine assays.

On a different day to their PET scans, participants underwent a T1-weighted structural MRI (Magnetom Trio Syngo MR B13 Siemens 3T; Siemens AG, Medical Solutions). Subjects completed the ICCAM fMRI imaging platform^{37,38} and these results will be reported elsewhere.

Image Analysis

As described previously ^{15,26,27}, image pre-processing and PET modelling were carried out using MIAKAT (www.miakat.org). Dynamic PET data underwent motion correction and rigid-body coregistration to the structural MRI. Ten bilateral Regions-of-interest (ROI) were chosen *a priori*: caudate, putamen, thalamus, cerebellum grey matter, frontal lobe grey matter, nucleus accumbens, anterior cingulate, amygdala, insular cortex and hypothalamus. All time-activity data, except the hypothalamus, were sampled using a neuroanatomical atlas ³⁹. This was applied to the PET image by non-linear deformation parameters derived using unified segmentation (SPM-12) of the structural MRI. The template and atlas fits were confirmed visually for each participant. The hypothalamus was manually defined on individual structural MRIs as previously described ^{15,39}.

[¹¹C]carfentanil BP_{ND} values were quantified using the simplified reference tissue model with occipital lobe as the reference region ^{15,40}. BP_{ND} is the ratio of specifically bound radioligand (e.g. bound to MOR) to that of non-displaceable radioligand (e.g. unbound and non-specifically or non-MOR bound [¹¹C]carfentanil) in tissue at equilibrium. BP_{ND} used in reference tissue methods compares the concentration of radioligand in receptor-rich with receptor-free regions ⁴¹. Reductions in [¹¹C]carfentanil BP_{ND} observed following dexamphetamine challenge are due to reductions in specific [¹¹C]carfentanil binding to MORs associated with endogenous opioid release, compared with non-specific [¹¹C]carfentanil binding in the occipital lobe reference region. Endogenous opioid release was indexed as the fractional reduction in [¹¹C]carfentanil BP_{ND} following dexamphetamine:

$$\Delta BP_{ND} = \frac{(BP_{NDpost} - BP_{NDpre})}{BP_{NDpre}}$$

Statistical Analysis

All statistical analyses were carried out using IBM SPSS (version 24). Data were normally distributed (Shapiro–Wilk) except for BDI and abstinence duration.

Demographic differences between groups were assessed using independent sample t-tests.

Omnibus mixed model ANOVA tested the effects of Status (AD or HC) on [¹¹C]carfentanil

BP_{ND} and ΔBP_{ND}, SAIRS and SSAI subjective responses, plasma amphetamine and serum

cortisol concentrations. Post-hoc tests were made using one-way ANOVA or t-tests.

Correlational analyses were made using Pearson correlation coefficient or Spearman's rho

(BDI and abstinence duration). Bonferroni corrected *p*-values are reported in the results.

Data were tested for sphericity, and where sphericity was violated ANOVAs were

Greenhouse-Geisser corrected.

RESULTS

Demographic and Clinical Variables

Demographic results are presented in *Table 1*. There were no significant differences in age or IQ between HC and AD participants. More AD participants smoked tobacco but there were no differences between daily numbers of cigarettes or dependence scores (FTND) between HC and AD smokers. AD participants had significantly higher BDI and STAI scores than HC but none reached a threshold for clinical anxiety or depression. UPPS-P negative urgency scores were higher in AD participants compared with HC.

Injected Mass and Radioactivity and Head Motion

There were no significant differences in injected cold carfentanil mass between AD participants and HC for either scan, but there was a significantly higher injected activity in post-dexamphetamine scans in AD participants (*Supplementary Table 1*). There were no significant correlations between [^{11}C]carfentanil BP_{ND} in any region and injected mass or activity in the pre- or post-dexamphetamine scans. There was no significant effect of dexamphetamine on movement within scans, or differences between AD and HC participants (*Supplementary Tables 2 and 3*).

Dexamphetamine and Cortisol Pharmacokinetics

A repeated measures ANOVA showed a significant effect of *Time* on dexamphetamine plasma concentrations but no significant effect of *Status* (AD or HC) (*Supplementary Figure 4, Supplementary Table 5*).

Serum cortisol concentration increased following oral dexamphetamine administration (*Supplementary Figure 6*). A mixed-model ANOVA showed a significant effect of *Time* on cortisol levels but no significant effect of *Status* (AD or HC) (*Supplementary Table 5*).

Subjective Effects of Amphetamine

The subjective effects from the oral dexamphetamine were mild in both groups (*Figure 1*). A mixed-model ANOVA showed no significant effects of *Time* or *Status* (AD or HC) on changes in SAIRS scores from baseline (*Supplementary Table 7*). There was a significant *Time x Status* interaction on change in SAIRS Anxiety from baseline. Post-hoc analysis (paired t-test) showed reductions in anxiety ratings in HC at 180 and 270 mins post-dexamphetamine ($p=0.048$ and $p=0.025$ respectively, Bonferroni corrected $p<0.01$) which was not present in the AD group. There was no significant effect of *Time* or *Status* on SSAI scores.

Pre- and Post-dexamphetamine [^{11}C]carfentanil BP_{ND}

A mixed-model ANOVA examining pre- and post-dexamphetamine [^{11}C]carfentanil BP_{ND} showed a significant effect of *Scan* (pre- or post-dexamphetamine) demonstrating differences in BP_{ND} following dexamphetamine, and a significant *Scan x Status* interaction indicating a significantly different change in BP_{ND} after dexamphetamine between AD and HC (*Supplementary Table 8*). Post-hoc paired t-tests showed significant reductions in BP_{ND} after oral dexamphetamine in HC across all ROIs except hypothalamus and amygdala, but no significant reductions in AD participants (*Supplementary Table 9*).

A mixed-model ANOVA examining pre-dexamphetamine [^{11}C]carfentanil BP_{ND} showed no significant effect of *Status* indicating no differences between AD and HC participants (*Figure 2, Supplementary Tables 8 and 9*).

A mixed-model ANOVA examining [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$ showed a significant effect of *Status*, indicating differences between AD and HC participants. Independent sample t-tests showed [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$ (i.e. opioid release) was significantly blunted in AD participants, compared with HC, in the frontal lobe, insula, thalamus, anterior cingulate and putamen (Bonferroni corrected $p < 0.005$) with large effect sizes (Cohen's $D > 0.8$, significant t-tests comparing [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$ between HC and AD) (*Figures 3 and 4, Supplementary Tables 8 and 9*).

[^{11}C]carfentanil binding, demographic and clinical variables

We found no significant correlations between [^{11}C]carfentanil BP_{ND} and $\Delta\text{BP}_{\text{ND}}$ with SADQ, TRQ, duration/length of alcohol abstinence or exposure measures in AD participants. Of note, AD did not report any AUQ craving at baseline or at any other point during the study. There were no significant differences in [^{11}C]carfentanil BP_{ND} or $\Delta\text{BP}_{\text{ND}}$ comparing smokers with non-smokers regardless of group (combined AD and HC or AD and HC separately). The inclusion of smoking status in the mixed-model ANOVA examining [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$ did not impact on these results (*Supplementary Table 8*). There were no significant correlations between [^{11}C]carfentanil BP_{ND} or $\Delta\text{BP}_{\text{ND}}$ with daily cigarettes smoked or FTND scores in all participants (AD and HC) or AD or HC separately.

There was no significant association between UPPS-P negative urgency and baseline [^{11}C]carfentanil BP_{ND} in AD or HC participants. There was a significant positive correlation between [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$ in the amygdala and BDI score (Spearman's $\rho=0.654$, $p=0.015$) in AD only, indicating a higher BDI score is associated with lower opioid release. This result did not survive Bonferroni correction (two-tailed $p<0.005$). There were no correlations between STAI and [^{11}C]carfentanil BP_{ND} or $\Delta\text{BP}_{\text{ND}}$ in either participant group.

MOR polymorphism

There was a higher G-allele prevalence in AD participants compared with HC (30.1% and 18.2% respectively – *Table 1*). To assess the influence of the OPRM1 A118G polymorphism on [^{11}C]carfentanil BP_{ND} the two mixed-model ANOVAs examining [^{11}C]carfentanil BP_{ND} and $\Delta\text{BP}_{\text{ND}}$ were repeated with the addition of the genotype (A:A or A:G/G:G) as a between-subject factor.

We found a significant main effect of *Genotype* on baseline [^{11}C]carfentanil BP_{ND} , but no *Status x Genotype* interaction. A post-hoc analysis independent sample t-test showed significantly lower [^{11}C]carfentanil BP_{ND} in G-allele carriers in the thalamus (two-tailed Bonferroni corrected $p<0.005$), and a trend towards lower [^{11}C]carfentanil BP_{ND} across all other regions (*Supplementary Figure 10, Tables 11 and 12*). We found no significant main effect of *Genotype* or *Status x Genotype* interaction on [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$.

DISCUSSION

We have demonstrated a blunted dexamphetamine-induced endogenous opioid release in the brain for the first time in abstinent alcohol dependent individuals with [¹¹C]carfentanil PET. We did not find higher baseline MOR availability in alcohol dependence as previously reported by ourselves and others ^{22,23,42}. Our data in alcohol dependence is consistent with our previous study in gambling disorder where we also found blunted dexamphetamine-induced opioid release ²⁷. This strongly suggests that dysregulation of opioid tone underpins both behavioural and substance addictions.

This 'opioid deficient' state may play a key role in a broader 'reward deficient' state associated with the development and maintenance of alcohol dependence and other addictions, and may precede the development of addiction ^{20,21,27,43–45}. Individuals with alcohol dependence or a family history of alcohol dependence both have blunted responses to financial rewards and lower peripheral plasma β -endorphin concentrations ^{43,44,46}. Although peripheral and central β -endorphin are not directly comparable, both are produced from the cleavage of pro-opiomelanocortin (POMC) and the release of both can be stimulated by intense exercise, dexamphetamine and alcohol ^{15,16,46–49}. This low opioidergic function may represent a vulnerability to the development of addiction which endures after successful treatment and may predispose an individual to relapse. There may be an additional impact of addiction or heavy alcohol use on endogenous opioid tone, though this is difficult to determine from our current [¹¹C]carfentanil PET studies.

1 There is evidence of blunted intravenous dexamphetamine-induced dopamine release in
2 alcohol dependence during early abstinence ⁵⁰, which may be a mechanism for the blunted
3 dexamphetamine-induced endogenous opioid release alcohol dependence. Another study
4 reported that lower dexamphetamine-induced ventral striatal dopamine release was
5 associated with blunted cortisol release ⁵¹. However, in our alcohol dependent participants
6 dexamphetamine-induced cortisol release was not blunted compared with controls. This
7 may suggest that dopamine responses to dexamphetamine are less blunted in our alcohol
8 dependent participants, with longer durations of abstinence, than those described in early
9 abstinence ⁵⁰.

10
11 The blunted dexamphetamine-induced endogenous opioid release in alcohol dependence
12 may be mediated by a mechanism downstream from dopamine release, which would be
13 consistent with the findings of blunted endogenous opioid release in gambling disorder
14 despite a higher dopamine response to oral dexamphetamine ^{27,52}. Intravenous
15 dexamphetamine increases striatal dopamine concentrations in man within minutes of
16 administration ^{50,53,54} but does not result in similarly acute changes in opioid levels in the
17 brain ⁵⁵. A period of 1.5 to 3 hours following dexamphetamine administration is required to
18 reach peak endogenous opioid concentrations ^{15,26,27,56,57}, suggesting that the mechanism of
19 dexamphetamine-induced endogenous opioid release is also downstream of the acute
20 dopamine release. Concentrations of other monoamines (5HT and noradrenaline) are also
21 increased by dexamphetamine, and may play a role in endogenous opioid release in brain
22 regions with lower dopamine transporter density, such as the frontal cortex and thalamus
23 ^{15,58}. Further work is required to better understand the mechanisms of dexamphetamine-

1 induced endogenous opioid release, and how this is blunted in both alcohol dependence
2 and gambling disorder.

3
4 The salience of our dexamphetamine 'reward' may also be a factor in mediating
5 endogenous opioid release. As addiction develops, salience towards addiction-associated
6 cues increases whilst responses to non-addiction related rewards decrease^{59,60}. For
7 example, individuals with alcohol dependence have blunted fMRI responses to non-salient
8 financial rewards and higher responses to salient alcohol cues^{43,44,61–63}. The effect of opioid
9 antagonists to modulate the mesolimbic system also appears to be mediated by the salience
10 of the reward. For example, naltrexone only blunts dexamphetamine-induced striatal
11 dopamine release in rats following a period of dexamphetamine sensitisation⁵⁴. Whilst
12 naltrexone does not modulate striatal fMRI response to financial reward anticipation in
13 alcohol dependence⁴³, when the same task was performed during an alcohol infusion, a
14 salient context, nalmeferene reduces activation¹¹. Naltrexone also reduces BOLD response in
15 striatum to salient alcohol cues in alcohol dependent individuals^{10,64}. This salience mediated
16 endogenous opioid release, rather than low opioidergic tone, may be the target for opioid
17 receptor antagonists in reducing the risk of relapse to heavy drinking during abstinence.

18
19 Whilst the above evidence suggests that salience is an important factor for the activation of
20 endogenous opioidergic signalling, a recent study has shown that feeding induces a release
21 of endogenous opioids regardless of how palatable or 'rewarding' the food is⁶⁵. One
22 potential further study to elucidate the effect of the salience of a reward on endogenous
23 opioid release in alcohol dependence would be the administration of an alcohol challenge,
24 where a non-blunted, or possibly enhanced, endogenous opioid release might be observed.

1 However, this would not be an ethical experiment to conduct in our abstinent alcohol
2 dependent participants.

3
4 Contrary to our hypothesis we did not find higher MOR availability in alcohol dependent
5 participants compared with controls. Previous studies using [¹¹C]carfentanil and
6 [¹¹C]diprenorphine have shown higher MOR in alcohol dependence, whilst in our data there
7 was no evidence of higher MOR availability in our alcohol dependent participants (*Figure 2*,
8 *Supplementary Table 9*)^{22–24}. Hermann *et al.*²⁵ reported non-significantly higher
9 [¹¹C]carfentanil binding in recently abstinent alcohol dependent individuals and lower MOR
10 receptor numbers in post-mortem alcohol dependent brains measured with the MOR
11 agonist [³H]DAMGO. They proposed that repeated alcohol administration in alcohol
12 dependence, and the subsequent chronic elevations in endogenous opioids, may lead to a
13 compensatory reduction in absolute MOR numbers²⁵. Chronic alcohol-induced endogenous
14 opioid release may also lower basal endogenous opioid tone via homeostatic feedback
15 mechanisms, potentially through an inhibition of POMC activity⁶⁶. This low endogenous
16 tone, when coupled with a cessation of alcohol-induced opioid release, may lead to a
17 relative increase in MOR availability in early abstinence, despite lower absolute MOR
18 density.

19
20 It is unclear if there are changes in basal endogenous opioid tone or MOR receptor numbers
21 as abstinence lengthens. Alcohol dependent participants in our current study have a
22 considerably longer abstinence compared with previous studies (months compared with
23 days to weeks)^{22–24} and have ‘normal’ MOR availability. This would be consistent with a
24 ‘normalisation’ of the balance of MORs and endogenous opioid ligands as abstinence

progresses. However, we did not observe any association between duration of abstinence and MOR availability in our current study and we and others have reported no changes in MOR or other opioid receptor availability in alcohol dependence during the first 3 months of abstinence^{22,23}. Higher MOR availability associated with higher craving reported previously in alcohol dependence may represent a greater potential to relapse, and a potential target for opioid receptor antagonist treatment. The lack of higher MOR availability in our alcohol dependent participants may reflect their stable abstinence and low craving, and suggests these individuals may benefit less from opioid receptor antagonist treatment compared with recently abstinent individuals reporting high alcohol craving.

We explored a number of clinical variables that may influence [¹¹C]carfentanil binding. Although smoking status differed in our alcohol dependent and control groups, there was no influence of current smoking, or associated measures, on baseline MOR availability or dexamphetamine-induced endogenous opioid release. Previous evidence concerning MOR in smokers is inconsistent, with higher, lower, or no differences in availability compared with non-smokers reported⁶⁷⁻⁶⁹. Consistent with others, we found that OPRM1 G-allele carriers had lower MOR availability^{70,71}. We found no significant effect of the OPRM1 polymorphism on dexamphetamine-induced endogenous opioid release, whilst others have observed lower endogenous opioid release in G-allele carriers during a pain task following placebo administration⁷¹. In gambling disorder we demonstrated a positive correlation between the UPPS-P negative urgency and baseline MOR availability in the caudate²⁷ but we did not replicate this finding in our alcohol dependent group. This is consistent with previous evidence showing correlations between impulsivity and [¹¹C]raclopride (D2/3) and [¹¹C]-(+)-PHNO (D₃-preferring) in gambling disorder and cocaine dependence but no such

1 correlations between [^{11}C]-(+)-PHNO binding and impulsivity in alcohol dependence ^{72–75}.

2 This suggests that the nature of impulsivity in alcohol dependence may differ from cocaine
3 and gambling disorders.

4
5 An exploratory analysis found that higher levels of depressive symptoms (BDI score) were
6 associated with a blunted endogenous opioid release in the amygdala, although this result
7 does not survive a strict Bonferroni correction for multiple correlations. The amygdala is an
8 important region for emotional processing in depression ⁷⁶, and endogenous opioid release
9 in the amygdala is associated with positive emotion and exercise induced negative emotion,
10 and is dysregulated in major depressive disorder ^{48,77–79}. One reason for this association
11 being observed only in alcohol dependent participants may be due to a higher and greater
12 range of BDI scores compared with controls. These scores were, however, low and did not
13 reach a threshold for clinically significant depression.

14
15 Our study was designed to be adequately powered for our primary outcome of
16 [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$ and our samples size is consistent with those in other relevant
17 published human PET literature examining amphetamine induced endogenous
18 neurotransmitter release ^{15,26,27,50,52,80}. Our study sample size is too small to adequately
19 investigate clinical factors that may be associated with our PET outcome measures.

20
21 In summary, we have demonstrated for the first time blunted dexamphetamine-induced
22 opioid release in the brain in abstinent alcohol dependent individuals. This study adds to the
23 evidence supporting a role for a dysregulated opioid system in alcohol dependence and
24 builds on our previous study with the same protocol in gambling disorder showing similarly

1 blunted dexamphetamine-induced opioid release in the presence of 'normal' MOR
2 availability. The similarly blunted opioid release in gambling disorder where participants had
3 no history of substance dependence, excluding nicotine, lends further support to an 'opioid
4 deficit' contributing to vulnerability to addiction. Thus, dysregulated opioid signalling
5 appears to be a common feature across both behavioural and substance addictions.
6
7 Further characterisation of the endogenous opioid tone and the dopamine–opioid
8 interactions will inform our understanding of substance and behavioural addictions and how
9 best to optimise and develop the use of opioid antagonists in treatment.

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CONFLICTS OF INTEREST:

- Professor Lingford-Hughes has received honoraria paid into her institutional funds for speaking and chairing engagements from Lundbeck, Lundbeck Institute UK and Janssen-Cilag. She has received research support from Lundbeck and has been consulted by but received no monies from Britannia Pharmaceuticals.
- Professor Nutt has consulted for, or received speaker's fees, or travel or grant support from the following companies with an interest in the treatment of addiction: RB pharmaceuticals, Lundbeck, GSK, Pfizer, D&A Pharma, Nalpharm, Opiant Pharmaceutical and Alkermes.
- Professor Gunn is a consultant for Abbvie and Cerveau.
- Dr Rabiner is a consultant for Opiant Pharmaceutical, AbbVie, Teva, and a shareholder in GSK.
- Professor Waldman has received honoraria from Bayer, Novartis, and GSK, and has been a consultant for Bayer.

Supplementary information is available at Molecular Psychiatry's website

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Table 1 – Demographic and genotype data (mean \pm SD)

	Healthy Controls	Alcohol Dependence	p-value (two-tailed)
Numbers	15	13	
Age	42.8 (\pm 10.2)	46.6 (\pm 7.3)	0.281
IQ	115.6 (\pm 9.9)	107.8 (\pm 10.7)	0.090
Alcohol UK units/week	6.67 (\pm 8.2)	0	
Current Smokers	3	7	
Cigarettes per day (current smokers)	10.0 (\pm 5.0)	10.6 (\pm 7.7)	0.247
Pack years (current and ex-smokers)	7.9 (\pm 8.1)	23.6 (\pm 14.5)	0.063
FTND (current smokers)	3.0 (\pm 2.7)	3.7 (\pm 3.1)	0.906
BDI on PET visit	0.2 (\pm 0.6)	3.3 (\pm 3.6)	0.004
STAI	30.3 (\pm 7.4)	37.2 (\pm 5.9)	0.012
SSAI (before PET 1)	27.9 (\pm 6.6)	28.8 (\pm 9.9)	0.797
UPPS-negative urgency	20.8 (\pm 6.1)	27.4 (\pm 4.1)	0.006
SADQ		38.5 (\pm 11.2)	
TRQ		18.9 (\pm 5.1)	
Alcohol Abstinence (days)	9.6 (\pm 12.7)	604.6 (\pm 866.5)	<0.001
OPRM1 G-allele carrier	2 of 11 (18.2%)	4 of 13 (30.1%)	

Abbreviations: Fagerstrom Test for Nicotine Dependence (FTND), Beck Depression Inventory (BDI), Spielberger State and Trait Anxiety Inventory (SSAI, STAI), UPPS Impulsivity Scale (UPPS), Severity of Alcohol Dependence Questionnaire (SADQ), Time to Relapse Questionnaire (TRQ)

FIGURES

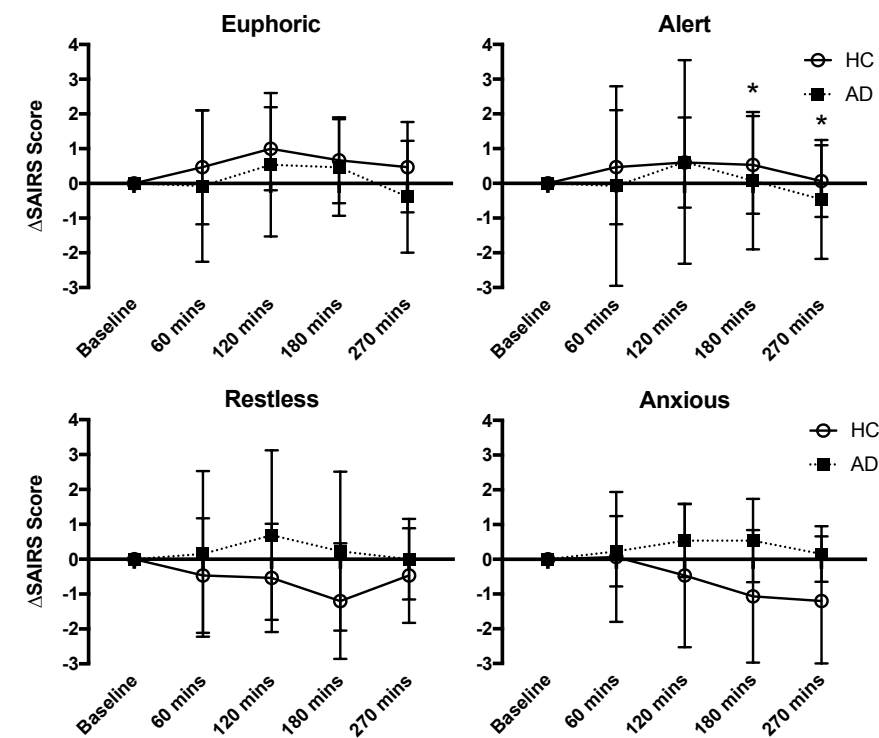


Figure 1 – Change in SAIRS following dexamphetamine administration (mean ± SD, *p<0.05 in HC)

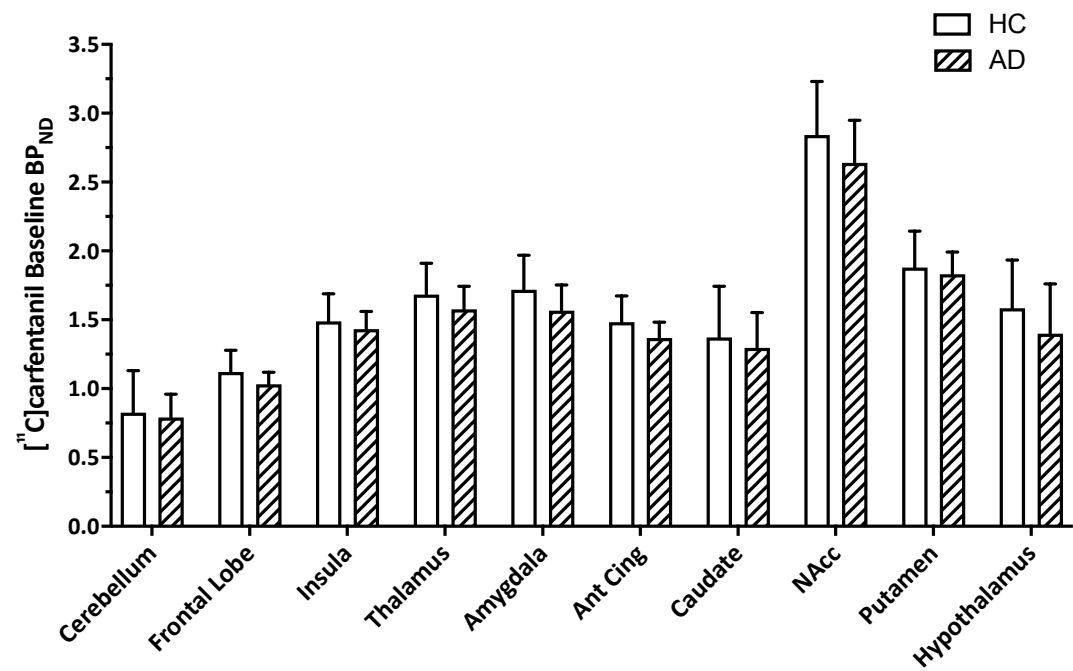


Figure 2 - Baseline [¹¹C]carfentanil BP_{ND} in HC and AD participants (mean ± SD)

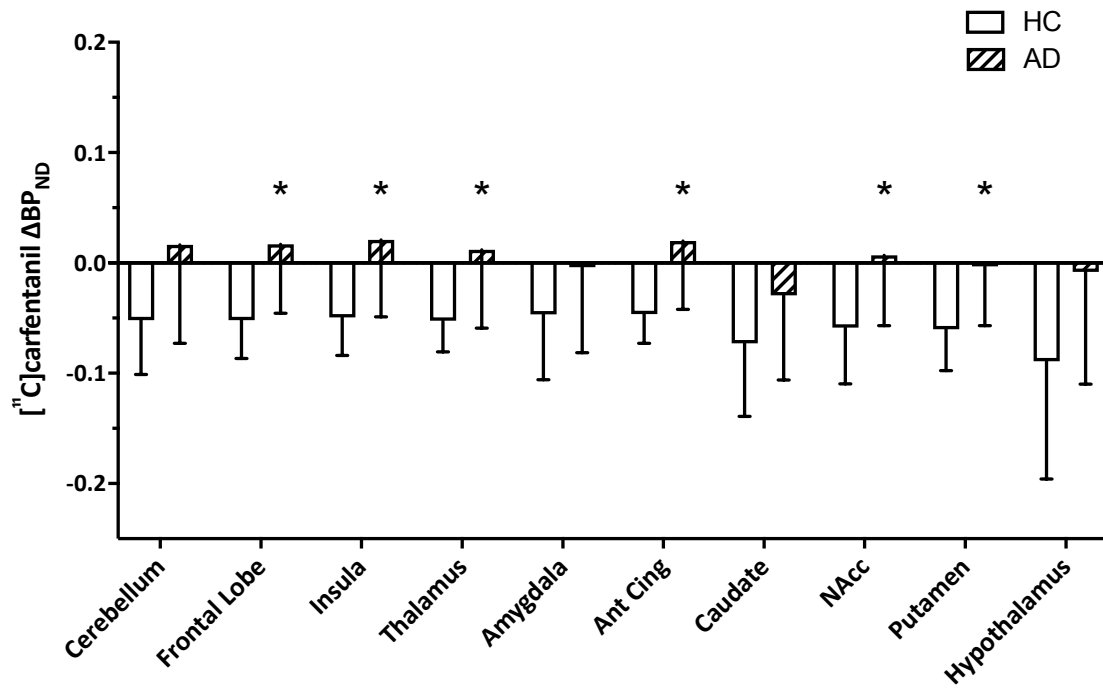


Figure 3 – $[^{11}\text{C}]$ carfentanil $\Delta\text{BP}_{\text{ND}}$ in HC and AD participants (mean \pm SD, *significant $\Delta\text{BP}_{\text{ND}}$ differences between HC and AD, Bonferroni corrected $p < 0.005$)

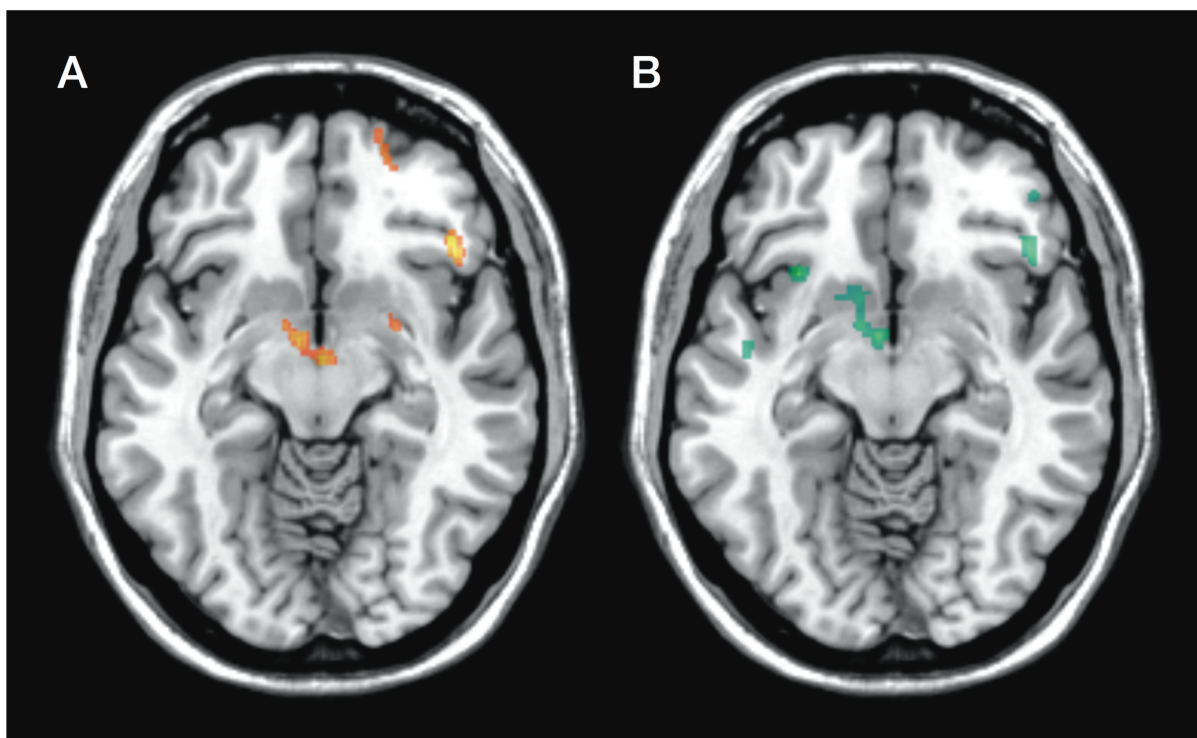


Figure 4A – Clusters with significant reductions in $[^{11}\text{C}]$ carfentanil BP_{ND} following dexamphetamine in HC. There are no significant clusters in AD.

Figure 4B – Clusters with significantly lower [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$ in AD compared with HC

(all images: min cluster size 100, $p < 0.001$, $z = 62$)

SUPPLEMENTARY DATA

Supplementary Table 1 – Injected [¹¹C]carfentanil cold mass and activity (Mean ±SD)

	Healthy Controls	Alcohol dependence	p-value (two-tailed)
Pre-dexamphetamine injected mass	1.33µg (±0.059)	1.69µg (±0.47)	0.093
Post-dexamphetamine injected mass	1.31µg (±0.58)	1.69µg (±0.39)	0.061
Pre-dexamphetamine injected activity	194.6mBq (±67.1)	218.3mBq (±48.8)	0.302
Post-dexamphetamine injected activity	197.0mBq (±65.3)	254.1mBq (±54.3)	0.019

Supplementary Table 2 – Global Movement Parameters Mean (±SD) values for within frame cumulative movement across PET scan on X,Y,Z axis (mm) and roll, pitch and yaw rotation (degrees).

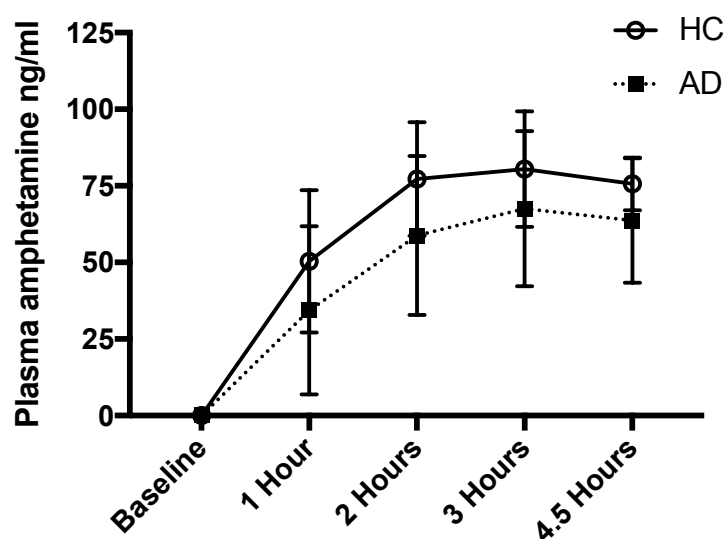
Movement Parameter	AD		HV	
	Pre	Post	Pre	Post
X	3.4 ±2.7	4.3 ±2.5	3.1 ±2.0	3.1 ±2.1
Y	11.6 ±7.5	11.8 ±6.9	11.5 ±12.3	12.2 ±7.2
Z	16.5 ±8.2	15.6 ±6.5	15.7 ±5.9	16.0 ±5.1
Roll	7.6 ±6.9	7.3 ±4.2	7.9 ±6.2	7.6 ±5.3
Pitch	2.2 ±1.6	2.6 ±1.8	2.4 ±1.9	2.0 ±1.3
Yaw	3.1 ±2.1	3.3 ±2.2	2.9 ±2.4	4.1 ±3.2

Supplementary Table 3 – Mixed Model ANOVA examining effect of Scan (pre- or post-dexamphetamine and Status (AD or HC) on Global Movement Parameters on X,Y,Z axis movement and roll, pitch and yaw rotation.

		F-ratio (effect <i>df</i> , error <i>df</i>)	p value
X, Y, Z model			
Within-subject effects	<i>Scan</i>	0.10 (1, 26)	0.755
	<i>Scan x Status</i>	0.01 (1, 26)	0.924
	<i>Movement</i>	17.9 (1.3, 33.0)	<0.001
	<i>Movement x Status</i>	0.06 (1.3, 33.0)	0.866
	<i>Scan x Movement</i>	0.61 (1.4, 36.0)	0.493
	<i>Scan x Movement x Status</i>	0.43 (1.4, 36.0)	0.579
Between-subject effects	<i>Status</i>	0.04 (1, 26)	0.853
Roll, Pitch, Yaw model			
Within-subject effects	<i>Scan</i>	0.06 (1, 26)	0.802
	<i>Scan x Status</i>	0.03 (1, 26)	0.870
	<i>Movement</i>	38.5 (1.8, 46.6)	<0.001
	<i>Movement x Status</i>	0.04 (1.8, 46.6)	0.945
	<i>Scan x Movement</i>	0.14 (1.3, 33.3)	0.775
	<i>Scan x Movement x Status</i>	0.27 (1.3, 33.3)	0.664

Between-subject effects	Status	0.03 (1, 26)	0.875
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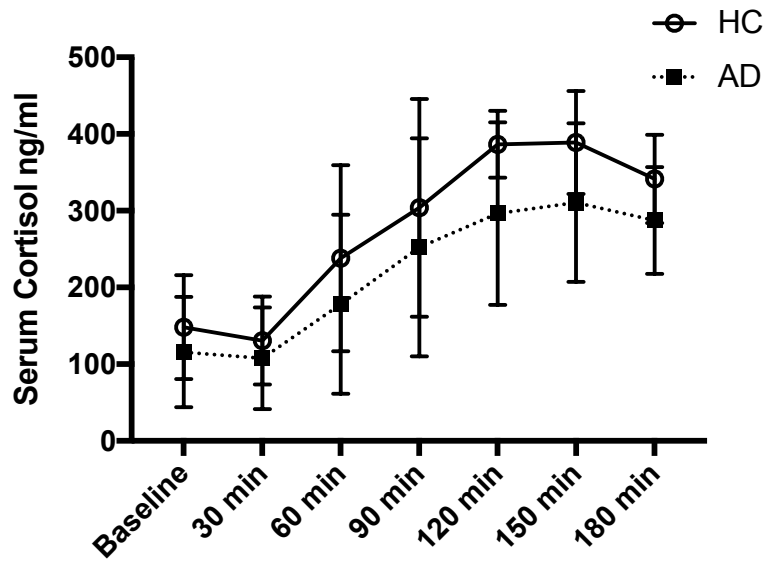
Supplementary Figure 4 – Plasma dexamphetamine concentrations (ng/ml) in HC and AD (mean \pm SD)



Supplementary Table 5 – Serum Cortisol and Plasma amphetamine concentrations mixed model ANOVA

		F-ratio (effect <i>df</i> , error <i>df</i>)	p value
Plasma Dexamphetamine			
Within-subject effects	Time	100.492 (2.6, 57.0)	<0.001
	Time x Status	1.323 (2.6, 57.0)	0.276
Between-subject effects	Status	4.047 (1, 22)	0.057
Serum Cortisol			
Within-subject effects	Time	25.115 (2.4, 36.3)	0.001
	Time x Status	0.381 (2.4, 36.3)	0.725
Between-subject effects	Status	1.602 (1, 15)	0.225

Supplementary Figure 6 – Dexamphetamine induced cortisol release in HC and AD (mean \pm SD)



Supplementary Table 7 – SAIRS mixed model ANOVA

		F-ratio (effect <i>df</i> , error <i>df</i>)	p value
Euphoria			
Within-subject effects	<i>Time</i>	2.510 (3.0, 79.1)	0.064
	<i>Time x Status</i>	0.584 (3.0, 79.1)	0.630
Between-subject effects	<i>Status</i>	1.154 (1, 26)	0.293
Alert			
Within-subject effects	<i>Time</i>	1.589 (2.8, 73.2)	0.202
	<i>Time x Status</i>	0.346 (2.8, 73.2)	0.780
Between-subject effects	<i>Status</i>	0.381 (1, 26)	0.543
Restless			
Within-subject effects	<i>Time</i>	0.809 (2.6, 66.4)	0.476
	<i>Time x Status</i>	1.408 (2.6, 66.4)	0.251
Between-subject effects	<i>Status</i>	2.838 (1, 26)	0.104
Anxiety			
Within-subject effects	<i>Time</i>	2.230 (3.0, 78.2)	0.091
	<i>Time x Status</i>	3.862 (3.0, 78.2)	0.012
Between-subject effects	<i>Status</i>	3.788 (1, 26)	0.062

Supplementary Table 8 – Results from mixed model ANOVAs examining [¹¹C]carfentanil BP_{ND} and ΔBP_{ND} in AD and HC participants

		F-ratio (effect <i>df</i> , error <i>df</i>)	p value
Pre- and post-dexamphetamine model in AD and HC			
Within-subject effects	<i>Scan</i>	13.145 (1, 26)	0.001
	<i>Scan x Status</i>	17.077 (1, 26)	<0.001
	<i>ROI</i>	212.457 (3.9, 102.2)	<0.001
	<i>ROI x Status</i>	0.455 (3.9, 102.2)	0.765
	<i>Scan x ROI</i>	1.839 (3.7, 94.9)	0.134
	<i>Scan x ROI x Status</i>	1.382 (3.7, 94.9)	0.249
Baseline BP_{ND} model in AD and HC			
Within-subject effects	<i>ROI</i>	224.1 (4.4, 114.7)	<0.001
	<i>ROI x Status</i>	0.700 (4.4, 114.7)	0.709
Between-subject effects	<i>Status</i>	2.336 (1, 26)	0.139
[¹¹C]carfentanil ΔBP_{ND} model in AD and HC			
Within-subject effects	<i>ROI</i>	2.054 (3.5, 91.1)	0.102
	<i>ROI x Status</i>	0.401 (3.5, 91.1)	0.782
Between-subject effects	<i>Status</i>	14.328 (1, 26)	0.001
[¹¹C]carfentanil ΔBP_{ND} model in AD and HC with smoking status as covariate			
Within-subject effects	<i>ROI</i>	1.581 (3.596, 86.311)	0.192
	<i>ROI x Status</i>	0.106 (3.596, 86.311)	0.973
	<i>ROI x Smoking</i>	0.311 (3.596, 86.311)	0.851
Between-subject effects	<i>Status</i>	11.067 (1,24)	0.003
	<i>Smoking</i>	0.159 (1,24)	0.693

Supplementary Table 9 – Pre- and post-dexamphetamine [¹¹C]carfentanil BP_{ND} and [¹¹C]carfentanil ΔBP_{ND} values (mean ±SD) in abstinent alcohol dependent and healthy control participants including Effect size calculations (Cohen's D) for significant ROI ΔBP_{ND} differences between AD and HC.

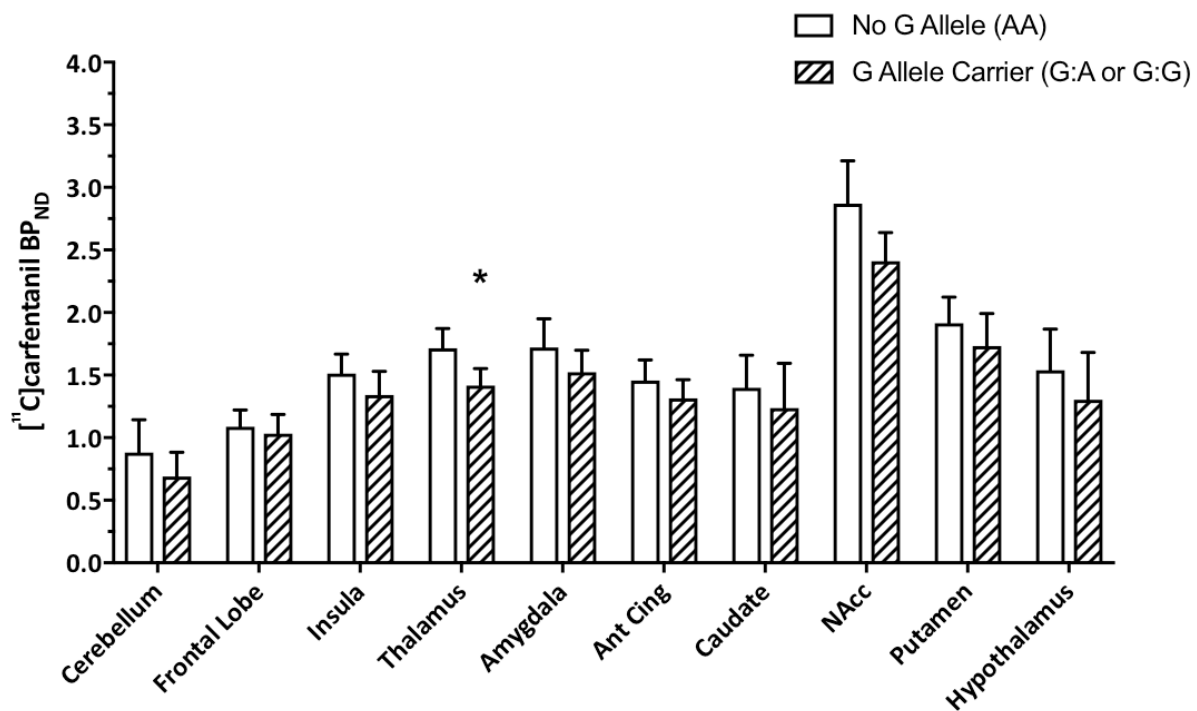
Region of interest	Pre-dexamphetamine [¹¹ C]carfentanil BP _{ND}		Post-dexamphetamine [¹¹ C]carfentanil BP _{ND}		[¹¹ C]carfentanil ΔBP _{ND}		
	AD	HC	AD	HC	AD	HC	Effect Size (Cohen's D)
Cerebellum	0.79 (±0.17)	0.83†† (±0.31)	0.80 (±0.16)	0.78†† (±0.29)	0.016* (±0.089)	-0.052* (±0.049)	0.94
Frontal Lobe	1.03 (±0.09)	1.12†† (±0.16)	1.05 (±0.12)	1.06†† (±0.15)	0.017** (±0.062)	-0.052** (±0.033)	1.36
Insula	1.43 (±0.13)	1.49†† (±0.20)	1.46 (±0.18)	1.41†† (±0.20)	0.021** (±0.070)	-0.049** (±0.034)	1.28
Thalamus	1.58 (±0.17)	1.68†† (±0.23)	1.59 (±0.17)	1.58†† (±0.22)	0.012** (±0.071)	-0.052** (±0.028)	1.19
Amygdala	1.57 (±0.19)	1.72† (±0.25)	1.56 (±0.18)	1.62† (±0.19)	-0.004 (±0.078)	-0.047 (±0.059)	0.62
Anterior Cingulate	1.37 (±0.11)	1.48†† (±0.19)	1.40 (±0.18)	1.41†† (±0.18)	0.020** (±0.062)	-0.046** (±0.027)	1.39
Caudate	1.30 (±0.26)	1.37†† (±0.37)	1.27 (±0.29)	1.27†† (±0.36)	-0.029 (±0.077)	-0.073 (±0.066)	0.61
NAcc	2.64 (±0.31)	2.84†† (±0.39)	2.66 (±0.37)	2.67†† (±0.35)	0.007* (±0.064)	-0.059* (±0.051)	1.13
Putamen	1.83 (±0.16)	1.88†† (±0.27)	1.82 (±0.18)	1.77†† (±0.30)	-0.003** (±0.054)	-0.060** (±0.037)	1.23
Hypothalamus	1.40 (±0.36)	1.58† (±0.35)	1.39 (±0.39)	1.47† (±0.44)	-0.008 (±0.102)	-0.089 (±0.107)	0.77

AD vs. HC * $p < 0.05$, ** $p < 0.005$

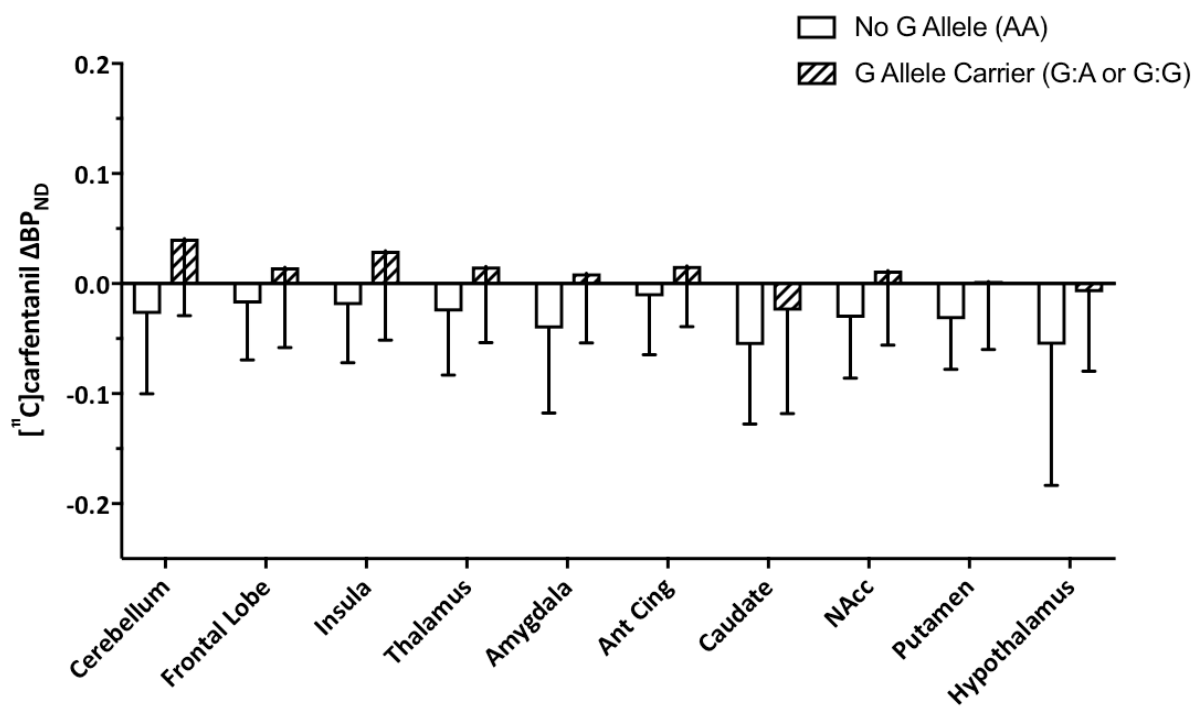
HC pre-dexamphetamine vs. HC post-dexamphetamine † $p < 0.05$, †† $p < 0.005$

Supplementary Figure 10

A – Effect of OPRM1 polymorphism on baseline [^{11}C]carfentanil BP_{ND} in whole study population (HC & AD) (A:A n=18, G:A/G:G n=6) (*differences in BP_{ND} between G allele and non-G allele carriers $p<0.005$, mean \pm SD)



B – Effect of OPRM1 polymorphism on [^{11}C]carfentanil $\Delta\text{BP}_{\text{ND}}$ in whole study population (HC & AD) (A:A n=18, G:A/G:G n=6, mean \pm SD)



Supplementary Table 11 – OPRM1 polymorphism mixed model ANOVA

		F-ratio (effect <i>df</i> , error <i>df</i>)	p value
Genotype and Baseline BP_{ND} model in AD and HC			
Within-subject effects	<i>ROI x Genotype</i>	1.573 (3.9, 78.1)	0.191
	<i>ROI x Status x Genotype</i>	0.921 (3.9, 78.1)	0.454
Between-subject effects	<i>Genotype</i>	5.651 (1, 20)	0.028
	<i>Status x Genotype</i>	0.018 (1, 20)	0.894
Genotype and ΔBP_{ND} model in AD and HC			
Within-subject effects	<i>ROI x Genotype</i>	0.266 (2.9, 58.5)	0.845
	<i>ROI x Status x Genotype</i>	0.693 (2.9, 58.5)	0.557
Between-subject effects	<i>Genotype</i>	1.791 (1, 20)	0.196
	<i>Status x Genotype</i>	0.472 (1,20)	0.500

Supplementary Table 12 – [¹¹C]carfentanil BP_{ND} values (mean ±SD) in individuals with A:A or A:G/G:G OPRM1 polymorphism and independent sample t-test p-value (two-tailed Bonferroni corrected p<0.005)

ROI	Genotype		p value
	A:A	A:G or G:G	
Cerebellum	0.88 (±0.25)	0.69 (±0.18)	0.114
Frontal Lobe	1.09 (±0.13)	1.03 (±0.14)	0.411
Insula	1.51 (±0.15)	1.34 (±0.17)	0.036
Thalamus	1.71 (±0.15)	1.42 (±0.12)	<0.001
Amygdala	1.72 (±0.22)	1.52 (±0.16)	0.068
Anterior Cingulate	1.46 (±0.16)	1.32 (±0.13)	0.076
Caudate	1.40 (±0.25)	1.24 (±0.33)	0.237
Nucleus Accumbens	2.87 (±0.33)	2.41 (±0.21)	0.006
Putamen	1.91 (±0.20)	1.73 (±0.24)	0.094
Hypothalamus	1.54 (±0.32)	1.30 (±0.34)	0.157

ARCHITECT serum Cortisol assay

This is a chemiluminescent microparticle immunoassay (CMIA) for the quantitative determination of cortisol in human serum, plasma or urine on the ARCHITECT iSystem. The ARCHITECT Cortisol assay is designed to have an assay precision of $\leq 10\%$ total CV for serum samples ≥ 3 to ≤ 35 $\mu\text{g/dL}$.

http://www.illexmedical.com/files/PDF/Cortisol_ARC.pdf

Dexamphetamine assay details

Alongside human plasma, quality control samples (spiked plasma at 40 mg/L) were analysed as part of each analytical sequence. Based on the results of the QC samples run throughout the duration study, the mean intra-assay coefficient of variance was 7.5%, the inter-assay coefficient of variance was 8.6%. The mean accuracy was 105%